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STUDIES OF AIR LOADS ON MAN

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OKLAHOMA CITY, OKLAHOMA

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STUDIES ON AIR LOADS ON MAN

JOHN J SWEARINGEN and ERNEST B McFADDEN

ABSTRACT

Data obtained in three different studies related to measurement of forces on the body due to air movement are summarized. The effects of short duration blast forces on personnel seated or standing at various distances from openings during pressure loss, blast forces necessary to disorient the body from numerous positions, effect of clothing on the drag forces, and measurements of forces and moments on the body during wind tunnel tests are discussed and compared.

INTRODUCTION

The purpose of this report is to summarize the findings of our laboratory on the effects of air loads (wind forces) on man. These findings are discussed in relation to the sudden failure of a small area in a pressure envelope, the physical displacement of man in corridor-like areas and the aerodynamics of man.

PRESSURE ENVELOPE FAILURE

Experiments by Swearingen[1] simulated failure of a window in a pressurized aircraft. The order of magnitude of safe distances of the occupant from the point of failure, i.e. the distance beyond which physical ejection or serious-to-fatal head injuries from impact are unlikely to occur, were shown. The tests involved rupturing a membrane in the window of a low pressure chamber (1350 ft^3 capacity), maintained from 2 to 7.5 lb/in^2 below atmospheric pressure with an articulated dummy seated near windows of various dimensions. Minimal safe distances for a pressure differential of 6 lb/in^2 are reproduced in Fig. 1. It was not possible with the facilities available

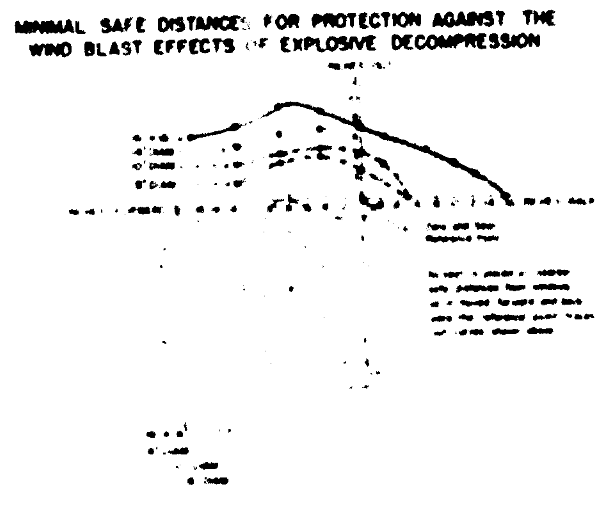


FIGURE 1. Minimal safe distance curves.

to reproduce closely the conditions of a window failure in flight, so the precise limits of distance for safety in various practical situations in aircraft remain unknown.

Subsequent experiments simulating failure of a large opening such as a door in a pressurized aircraft were also made using one subject.

The subject, wearing a safety harness attached to a slack cable, stood 24 in. in front of and facing a 75 in. by 37 in. opening covered by a diaphram pressurized to 6.5 lb/in^2. The forces were surprisingly low despite the distance, relative sizes, and pressure differential involved. He was not blown from his feet but maintained balance by stepping forward. This might suggest that personnel working near pressurized doors could be protected by a simple restraining cable, if a need for this arose. The peak force in this experiment was found to be about 170 lb.

In chambers of larger size than the one used (1350 ft^3), air loads would last longer and thereby have a greater tendency to displace the body. For continuous air loads equal to the magnitude of the maximum experienced in a decompression from a sea level equivalent to a pressure 6.5 lb/in^2 lower, the magnitude of the air load is estimated in Appendix I to be about twice that experienced here.

PHYSICAL DISPLACEMENT OF MAN BY AIR BLAST

One of the purposes of this series of experiments was to determine the magnitude of short duration air loads that would cause the subjects to lose their balance or to be otherwise physically displaced. The experiments were conducted in a space similar to corridor areas in aircraft as shown in Fig. 2. The duration of these forces was several tenths of a second. Figure 3 gives a sample oscillograph tracing. The various body positions studied are illustrated in Fig. 4. Note in Fig. 4 that shadographs were made of nude (shorts and shoes) subjects in order to obtain a sharp outline for area determinations.

Phase 1. Measurement of Drag Forces

This study included measurement of maximum forces acting on the clothed human body (shirt, trousers and shoes) during equalization of a pressure difference of 6.5 lb/in^2 following puncture of a membrane separating a partially evacuated low-pressure chamber and a "wind tunnel" or collar at sea level pressure. The subjects assumed an upright or other position in the rectangular "wind tunnel" with the body oriented in various directions in relation to the air blast. The subject was supported upon a

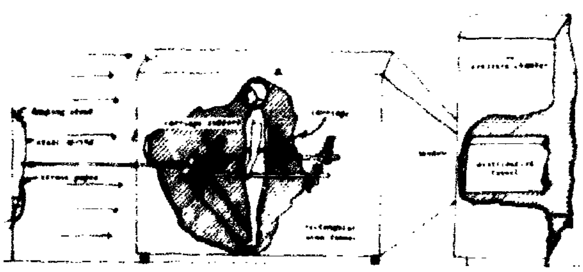


Figure 2. Mockup for measuring forces of wind blast on human subjects.

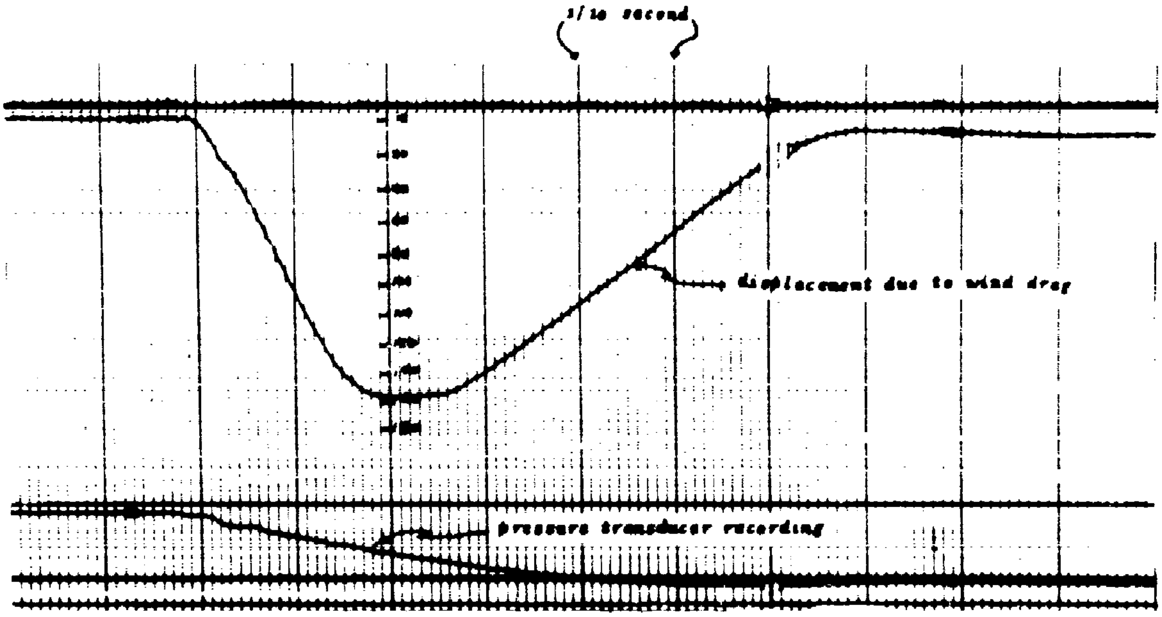


FIGURE 3. Sample oscillograph tracing.

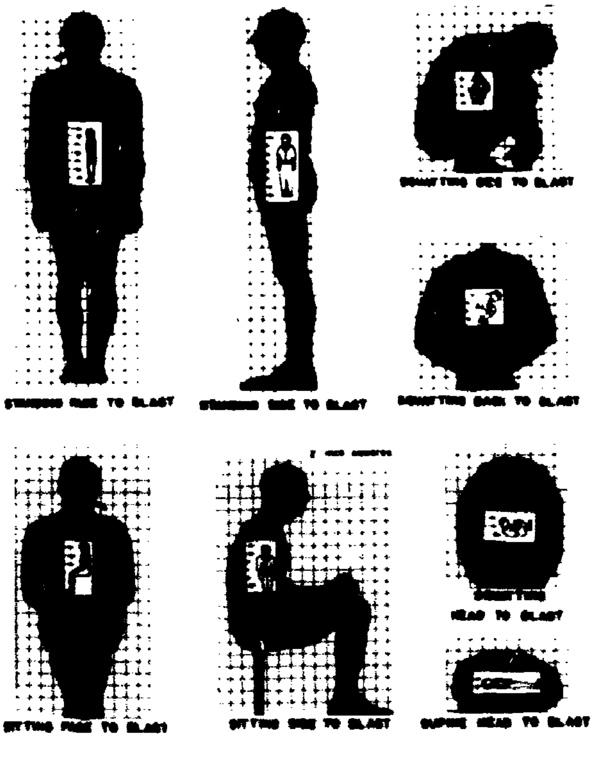
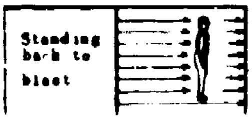
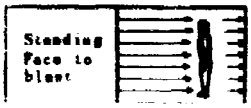
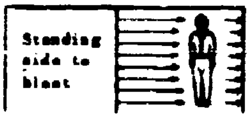
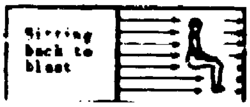
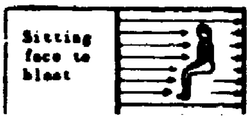
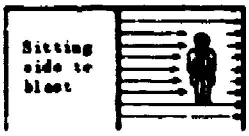
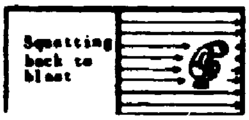
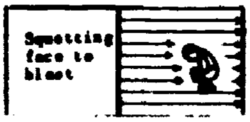
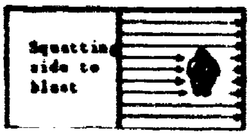
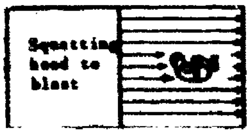
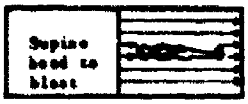


FIGURE 4. Projected areas of human subjects.

TABLE 1.
Wind Blast Forces on the Human Body (Phase 1)

Body Position	Subject	Force (in lbs) average 5-8 trials	Projected Body Area (Sq. Ft.)	Equivalent Flat Plate Area (Sq.Ft.)	AI/AP
 Standing back to blast	S	177.3	6.38	4.85	.76
	M	217.0	7.44	5.23	.70
	A	164.8	6.08	4.68	.77
	B	162.6	6.08	4.63	.76
	C	193.3	6.97	5.02	.72
	Av.	183.0	6.59	4.88	
 Standing face to blast	S	156.2	6.38	4.53	.71
	M	185.0	7.44	4.93	.66
	A	152.8	6.38	4.45	.73
	B	146.6	6.08	4.35	.72
	C	171.6	6.97	4.78	.69
	Av.	162.4	6.59	4.60	
 Standing side to blast	S	66.8	3.88	2.48	.64
	M	79.0	4.61	2.83	.61
	A	74.2	3.91	2.70	.69
	B	73.0	3.97	2.65	.67
	C	82.6	4.52	2.92	.65
	Av.	75.1	4.18	2.71	
 Sitting back to blast	S	86.0	4.27	3.00	.70
	M	94.4	4.96	3.23	.65
	A	80.6	4.19	2.88	.69
	B	106.2	4.27	3.51	.82
	C	105.4	4.63	3.49	.75
	Av.	94.5	4.46	3.22	
 Sitting face to blast	S	84.2	4.27	2.97	.70
	M	107.8	4.94	3.53	.71
	A	90.2	4.19	3.13	.75
	B	90.0	4.27	3.12	.73
	C	105.0	4.63	3.48	.75
	Av.	95.4	4.46	3.24	
 Sitting side to blast	S	72.0	4.02	2.63	.65
	M	77.6	4.77	2.79	.58
	A	64.6	3.83	2.42	.63
	B	76.2	3.91	2.75	.70
	C	76.0	4.33	2.74	.63
	Av.	73.2	4.17	2.66	
 Squatting back to blast	S	47.6	3.50	1.88	.54
	M	50.6	3.88	1.98	.51
	A	45.5	2.52	1.81	.72
	B	50.6	2.72	1.98	.73
	C	53.8	3.61	2.08	.58
	Av.	49.6	3.25	1.94	
 Squatting face to blast	S	64.0	3.50	2.40	.69
	M	102.6	3.88	3.42	.88
	A	57.8	2.52	2.08	.83
	B	76.5	2.72	2.75	1.01
	C	72.8	3.61	2.65	.73
	Av.	73.9	3.25	2.66	
 Squatting side to blast	S	62.2	3.61	2.35	.65
	M	84.6	4.47	2.98	.67
	A	74.8	3.54	2.72	.77
	B	78.4	4.05	2.82	.70
	C	76.4	4.02	2.76	.69
	Av.	75.2	3.94	2.72	
 Squatting head to blast	S	38.0	2.86	1.54	.54
	M	44.2	3.52	1.77	.50
	A	38.4	2.45	1.57	.64
	B	41.8	2.90	1.68	.58
	C	53.4	3.43	2.07	.60
	Av.	43.1	3.03	1.72	
 Supine head to blast	S	43.2	1.37	1.73	1.26
	M	55.2	2.02	2.13	1.06
	A	45.2	1.22	1.80	1.48
	B	44.6	1.44	1.77	1.23
	C	55.2	1.72	2.13	1.24
	Av.	48.6	1.55	1.91	

carriage mount, one end of which was linked to a heavy steel spring to which strain gauges were affixed for measurement of forces (Fig. 2). Table I summarized the averages of five to eight trials on each of five experimental subjects. Eleven different body positions were tested. It was expected that the forces acting on the body would vary between subjects and would be roughly related to body sizes.

The column "Projected Body Area" of Table I represents the area of the silhouette of each subject in each position assumed.

Measurements were also made of the forces acting on a series of flat plates of various sizes placed in the wind tunnel on the human subject carriage. These are shown graphically in Fig. 5. The third column of figures in Table I represents the flat plate area equivalent of the force measured on the human subject. The last column of Table I represents the ratio of the equivalent flat plate area to the projected area of the body.

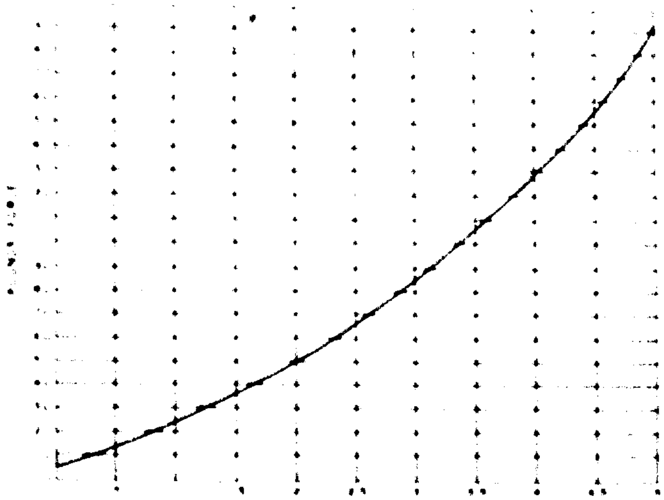


FIGURE 5. Flat plate resistance to wind blast (33 cm Hg Diff.).

TABLE II
Summary of Force Data Obtained in Wind Blast Study (Phase 2)

[illegible]

PHASE 2. BLAST FORCES PRODUCING DISORIENTATION

Another series of fifty tests was made on one subject (clothed) as an initial step in the accumulation of data on the forces required to disorient man from standing and seated posture, and while walking with face, back and side to the blast. In these tests repeat measurements were made of the maximum forces acting on the human body at successive increments of window pressure differential. These pressure differentials on the window ranged from 5.5 to 44.0 cm Hg, in 5.5 cm Hg increments. After establishing these values for the single subject, he assumed the same positions in the wind tunnel without attachment to strain gauges or other force measuring devices. The subject was secured by a safety belt and slack cable to minimize the danger of bodily injury. A series of trials was made increasing the pressure differential in successive trials until the subject was unable to maintain balance or to recover. The criteria for not being able to recover his body position was falling beyond a possible point of balance at the extreme range of the safety harness. Table II shows the effect of wind blast upon maintenance of body posture. Table III presents force calibration measurements on the subject at eight window pressure differentials.

TABLE III

Changes of Wind Blast Forces (lb) on the Human Body Due to Changes of Pressure Differential

Subject: A

	Standing			*Sitting*		
Differential pressure in cm Hg	*Back to blast*	*Face to blast*	*Side to blast*	*Back to blast*	*Face to blast*	*Side to blast*
5.5	21	12	2	0	7	6
11.0	69	59	14	25	31	20
16.5	116	96	29	47	45	37
22.0	143	125	48	58	63	55
27.5	166	154	75	71	77	63
33.0	174	172	77	84	82	75
38.5	179	180	85	88	86	80
44.0	184	182	82	92	91	85

PHASE 3. EFFECTS OF CLOTHING ON DRAG FORCES

The final phase was concerned with the effects of clothing on the drag of the human body. To determine the component of the drag forces presented in Phases 1 and 2 which could be attributed to the clothing, additional tests were made with subjects wearing shorts and shoes. Results are reproduced in Table IV and show that drag forces are 17-22 per cent less for nude individuals. This difference in drag for clothed and nude subjects has been confirmed in wind tunnel studies by Schmitt[4] who found 17-20 per cent difference during long exposures to constant air loads.

TABLE IV

Effects of Clothing on Drag Forces, Standing Back to Blast, 33 cm Hg Diff.

	With shirt, trousers and shoes	*With shorts and shoes*	*Difference*
Subject A	177.0 lb	138.0 lb	39 lb
	177.3*	138.0	
Subject B	177.0	140.0	37
	162.6*	139.0	
Subject C	210.0	173.0	37
	193.3*	173.0	

*Average of numerous trials in Phase 1.

AERODYNAMICS OF MAN

The experimental results reported in the previous section were obtained during very brief exposures to air loads. Because it was desirable to know whether these results would hold during long exposures and for related reasons, the Aerodynamics Laboratory of the David W. Taylor Model Basin was approached through the Navy Department and agreed to make aerodynamic measurements on human subjects in their wind tunnel. Schmitt[4] reported the findings obtained in tests done in collaboration with FAA personnel. Drag coefficients and lift, side force and moments to indicate relative trends of motion for each of five body positions (standing, sitting, supine and two squat positions) were determined.

The drag coefficients (C_D) which are of more immediate application to the purpose of the present report are given in terms of the body parameter vH/S which was selected from five trial parameters as giving the least variation in drag coefficients (v = volume of the body in ft³, H = height in ft, S = body surface area in ft²). The values of this parameter for the 16 subjects of these tests varied from 0.65 to 0.82 ft², with a mean value for the group of 0.72 ft².

Schmitt also reported dynamic pressures (q) with corresponding airspeeds and Reynolds numbers. These are reproduced in Table V. Drag coefficients were found to be practically independent of the Reynolds number within the range of test, except below a Reynolds number of 0.5×10^6, where a sharp increase in drag coefficient was found.

TABLE V

Summary of Test Dynamic Pressures with Approximate Corresponding Airspeeds and Reynolds Numbers

q lb/ft²	V ft/sec	V knots	$R \times 10^{-6}$
1.0	30.1	17.8	0.17
9.0	90.2	53.4	0.51
26.0	153	90.8	0.87
37.0	183	108	1.04
43.0	195	116	1.14
50.0	212	126	1.21
58.0	227	134	1.32
66.0	243	144	1.39

With the above information, drag force (D) can be calculated from the determined coefficients of drag using the equation, $D = C_D \times (vH/S) \times q$. This calculation, of course, requires that the airspeed which is needed to obtain values for q be known.

Unfortunately, airspeed values at various points in an airplane or other pressurized vessel undergoing decompression are not usually available. However, some estimate of airspeeds can generally be made. For example, in the studies on the physical displacement of man reported in the previous section, the following reasoning may be applied: (a) since the ratio of the area of the ruptured window to the cross-sectional area of the corridor or "wind tunnel" was approximately 0.13, the airspeed in the corridor was 0.13 of that at the window, (b) the airspeed at the window may be estimated at 886 ft/sec from the equation for the efflux of gases ($v = \sqrt{2P/\rho}$) and (c) the airspeed in the unoccupied tunnel was about $0.13 \times 886 = 118$ ft/sec. Using this estimate of airspeed and the mean value of 0.72 for vH/S, drag forces are calculated from the DTMB data and compared in Table VI with the data on clothed subjects given in the section on the physical displacement of man. Excepting the supine position, there is agreement between the observed and calculated values. More experience in this relatively unexplored field is needed to judge how well calculated and observed results might be expected to agree in such a situation. For example, the method used to calculate airspeed at the point of entry to the corridor would have over-estimated this quantity. This over-estimate may have approximately compensated for the fact that the subjects occupied an appreciable portion of the cross-sectional area of the corridor.

TABLE VI

Comparing Calculated Drag Forces From Wind Tunnel Tests With Observed Values in Short Duration Blast Studies

Posture	Angle	Drag coeff. (DTMB data)	Drag Calc	Drag Obs	Obs/Calc
Standing	0	12.0	136	162	1.2
	90	5.0	57	75	1.3
	180	11.0	125	183	1.5
Sitting	0	7.8	88	95	1.1
	90	4.4	50	73	1.5
	180	7.0	79	95	1.2
Supine	0	1.5	17	49	2.9
Squat No. 1	180	2.5	28	43	1.5
Squat No. 2	0	4.3	49	74	1.5
	90	3.5	40	75	1.9
	180	3.0	34	50	1.5

In any event it should not be inferred from the above results that forces on the body due to air movement can be readily calculated from the DTMB data for all practical situations. Actually, such calculations only apply accurately to conditions of uniform airspeed in a relatively unconfined space. In such practical situations as are discussed in this report in connection with airplane decompression, it cannot necessarily be assumed that such conditions are approached. An extreme example of a situation in which these calculations could not be used would be the case where an opening was completely occluded by a person. In this case, the force on the body would be estimated by multiplying static pressure by the area of the body involved. However, except for such an extreme case, the DTMB data can be used to make order-of-magnitude estimates which are helpful, for example, in designing experiments to measure directly the magnitude of force that air movement exerts on man in particular situations.

APPENDIX

Calculation of Airloads on Man Standing Near A Door During Decompression Due to Door Failure

The values needed for calculating drag force from the equation, $D = (vH/S) \times C_D \times q$ are given below:

$$\frac{vH}{S} = 0.71$$

$C_D = 11$ (from the DTMB report)

NOTE: This is the value for a clothed individual facing the door.

To obtain q, an estimate must be made of the airspeed at the point where the subject stood. The velocity at the door may be taken as 886 ft/sec according to a previous estimate for a pressure differential of 6.5 lb/in^2 (see test). The effective cross-sectional area where the subject stood can be taken as a first approximation to be equal to the width of the door (37 in.) $\times$ the height of the chamber (96 in.) or 3552 in. plus twice the length of a quarter circle 30 in. in radius $\times$ the height of the chamber or 9043 in^2, which gives a total of 12,595 $in.^2$ A 30 in. radius instead of a 24 in. radius (the distance between the frontal plane of the subject and the door) is taken to allow for the thickness of the body. In this approximation, the two quarters of the cylindrical surface are visualized as being positioned at the two sides of the door. The area of the doorway is 2886 in^2 or 0.23 of the effective area, which gives an estimated airspeed at this point of 0.23 $\times$ 886 or 204 ft/sec, and a q value of 47 lb/ft^2.

Substituting these values, we have

$$D = 0.71 \times 11 \times 47 = 367 \text{ lb}$$

This value is considerably greater than the 166-174 lb (Table II) force found necessary to displace a person standing with his back to the wind. The explanation of this discrepancy presumably is that the duration of airload in the experiments facing the door was shorter than the duration of airloads in which the forces causing body displacement were measured. As suggested in the text, considerable judgment must be used in applying to a given situation experimental data obtained under other conditions, or in using drag coefficients to calculate reliable estimates of forces.

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2. Schmitt, T. J., Wind Tunnel Investigations of Air Loads on Human Beings. Report 892, Aero 858, Navy Department, The David W. Taylor Model Basin Aerodynamics Laboratory, Washington 7, D.C., January 1954.

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